

SCATTERED PILOT PATTERN AND CHANNEL ESTIMATION METHOD FOR  
MIMO-OFDM SYSTEMS  
RELATED APPLICATION

This application claims the benefit of U.S.  
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FIELD OF THE INVENTION

This invention relates to OFDM communication  
systems, and more particularly to a more efficient use of  
10 pilot symbols within such systems.

BACKGROUND OF THE INVENTION

Multiple Input Multiple Output - Orthogonal  
Frequency Division Multiplexing (MIMO-OFDM) is a novel  
highly spectral efficient technology used to transmit high-  
15 speed data through radio channels with fast fading both in  
frequency and in time.

In wireless communication systems that employ  
OFDM, a transmitter transmits data to a receiver using many  
sub-carriers in parallel. The frequencies of the sub-  
20 carriers are orthogonal. Transmitting the data in parallel  
allows the symbols containing the data to be of longer  
duration, which reduces the effects of multi-path fading.  
The orthogonality of the frequencies allows the sub-carriers  
to be tightly spaced, while minimizing inter-carrier  
25 interference. At the transmitter, the data is encoded,  
interleaved, and modulated to form data symbols. Overhead  
information is added, including pilot symbols, and the  
symbols (data plus overhead) are organized into OFDM  
symbols. Each OFDM symbol typically uses  $2^n$  frequencies.

Each symbol is allocated to represent a component of a different orthogonal frequency. An inverse Fast Fourier Transform (IFFT) is applied to the OFDM symbol (hence the preference of  $2^n$  frequencies) to generate time samples of a signal. Cyclic extensions are added to the signal, and the signal is passed through a digital-to-analog converter. Finally, the transmitter transmits the signal to the receiver along a channel.

When the receiver receives the signal, the inverse operations are performed. The received signal is passed through an analog-to-digital converter, and timing information is then determined. The cyclic extensions are removed from the signal. The receiver performs an FFT on the received signal to recover the frequency components of the signal, that is, the data symbols. Error correction may be applied to the data symbols to compensate for variations in phase and amplitude caused during propagation of the signal along the channel. The data symbols are then demodulated, de-interleaved, and decoded, to yield the transmitted data.

In systems employing differential detection, the receiver compares the phase and/or amplitude of each received symbol with an adjacent symbol. The adjacent symbol may be adjacent in the time direction or in the frequency direction. The receiver recovers the transmitted data by measuring the change in phase and/or amplitude between a symbol and the adjacent symbol. If differential detection is used, channel compensation need not be applied to compensate for variations in phase and amplitude caused during propagation of the signal. However, in systems employing coherent detection the receiver must estimate the

actual d phase and amplitude of the channel response, and channel compensation must be applied.

The variations in phase and amplitude resulting from propagation along the channel are referred to as the channel response. The channel response is usually frequency and time dependent. If the receiver can determine the channel response, the received signal can be corrected to compensate for the channel degradation. The determination of the channel response is called channel estimation. The inclusion of pilot symbols in each OFDM symbol allows the receiver to carry out channel estimation. The pilot symbols are transmitted with a value known to the receiver. When the receiver receives the OFDM symbol, the receiver compares the received value of the pilot symbols with the known transmitted value of the pilot symbols to estimate the channel response.

The pilot symbols are overhead, and should be as few in number as possible in order to maximize the transmission rate of data symbols. Since the channel response can vary with time and with frequency, the pilot symbols are scattered amongst the data symbols to provide as complete a range as possible of channel response over time and frequency. The set of frequencies and times at which pilot symbols are inserted is referred to as a pilot pattern. The optimal temporal spacing between the pilot symbols is usually dictated by the maximum anticipated Doppler frequency, and the optimal frequency spacing between the pilot symbols is usually dictated by the anticipated delay spread of multi-path fading.

The existing pilot-assisted OFDM channel estimation approaches are designed for conventional one

transmitter system. With a scattered pilot arrangement, there are three classes of algorithms:

- 1-D frequency interpolation or time interpolation
- Transformed frequency 1-D interpolation

- 5     • Independent time and frequency 1-D interpolation

10     The first class of algorithms is based on the pilot OFDM symbol (all the sub-carriers are used as the pilots) or comb-type of pilots. This approach shown in the flow chart of Figure 1A is simple but only suitable for channels with high frequency selectivity or channels with high time fading. The method involves pilot extraction in the frequency domain (step 1A-1) followed by interpolation in time (step 1A-2), or interpolation in frequency (step 1A-3).

15     The second method shown in the flow chart of Figure 1B is aimed for channels with slow Doppler fading and fast frequency fading. It improves the first method by using FFT to reconstruct the channel response back to time domain for noise reduction processing at the expense of FFT/IFFT  
20     computing for the channel estimation separately. The method begins with pilot extraction in the frequency domain (step 1B-1) , which may be followed by interpolation in frequency (step 1B-2). Then an inverse fast Fourier transform (step 1B-3) , smoothing/de-noise processing (step 1B-4) , and finally a  
25     fast Fourier transform (1B-5) steps are executed.

   The third method shown in the flow chart of Figure 1C can be used to estimate channel for mobile applications, where both fast time fading and frequency fading exist. However it needs a relatively high density of pilots and a

completed interpolator. This method involves pilot extraction in the frequency domain (step 1C-1) this is followed by interpolation in time (step 1C-2) and interpolation in frequency (step 1C-3).

5 In the propagation environment with both high frequency dispersion and temporal fading, the channel estimation performance can be improved by the increase of pilot symbol density at the price of the reduction of the spectral efficiency of the data transmission. To interpolate  
10 and reconstruct the channel response function from the limited pilots to achieve reliable channel estimation with the minimum overhead is a challenging task.

There are a variety of existing standard pilot patterns. In environments in which the channel varies only  
15 slowly with time and frequency, the pilot symbols may be inserted cyclically, being inserted at an adjacent frequency after each time interval. In environments in which the channel is highly frequency dependent, the pilot symbols may be inserted periodically at all frequencies simultaneously.  
20 However, such a pilot pattern is only suitable for channels that vary very slowly with time. In environments in which the channel is highly time dependent, the pilot symbols may be inserted continuously at only specific frequencies in a comb arrangement to provide a constant measurement of the  
25 channel response. However, such a pilot pattern is only suitable for channels that vary slowly with frequency. In environments in which the channel is both highly frequency and highly time dependent (for example, mobile systems with much multi-path fading), the pilot symbols may be inserted  
30 periodically in time and in frequency so that the pilot

symbols form a rectangular lattice when the symbols are depicted in a time-frequency diagram.

In OFDM communication systems employing coherent modulation and demodulation, the receiver must estimate the channel response at the frequencies of all sub-carriers and at all times. Although this requires more processing than in systems that employs differential modulation and demodulation, a significant gain in signal-to-noise ratio can be achieved using coherent modulation and demodulation. The receiver determines the channel response at the times and frequencies at which pilot symbols are inserted into the OFDM symbol, and performs interpolations to estimate the channel response at the times and frequencies at which the data symbols are located within the OFDM symbol. Placing pilot symbols more closely together (in frequency if a comb pattern is used, in time if a periodic pattern is used, or in both frequency and in time if a rectangular lattice pattern is used) within a pilot pattern results in a more accurate interpolation. However, because pilot symbols are overhead, a tighter pilot pattern is at the expense of the transmitted data rate.

Existing pilot patterns and interpolation techniques are usually sufficient if the channel varies slowly with time (for example for nomadic applications). However, if the channel varies quickly with time (for example, for mobile applications), the time interval between pilot symbols must be reduced in order to allow an accurate estimation of the channel response through interpolation. This increases the overhead in the signal.

The problem of minimizing the number of pilot symbols while maximizing the accuracy of the interpolation

is also particularly cumbersome in Multiple-Input Multiple-Output (MIMO) OFDM systems. In MIMO OFDM systems, the transmitter transmits data through more than one transmitting antenna and the receiver receives data through more than one receiving antenna. The binary data is usually divided between the transmitting antennae, although the same data may be transmitted through each transmitting antenna if spatial diversity is desired. Each receiving antenna receives data from all the transmitting antennae, so if there are  $M$  transmitting antennae and  $N$  receiving antennae, then the signal will propagate over  $M \times N$  channels, each of which has its own channel response. Each transmitting antenna inserts pilot symbols into the same sub-carrier location of the OFDM symbol which it is transmitting. In order to minimize interference at the receiver between the pilot symbols of each transmitting antenna, each transmitting antenna typically blinks its pilot pattern on and off. This increases the temporal separation of the pilot symbols for each transmitter, reducing the accuracy of the interpolation used to estimate the channel response. In MIMO-OFDM systems a simple and fast channel estimation method is particularly crucial because of the limitation of the computational power for estimating  $M \times N$  channels, while in SISO-OFDM system only one channel needs to be estimated.

## SUMMARY OF THE INVENTION

Channel estimation methods are provided which are based on the partial interpolation of a scattered pilot by using true 2-D interpolation; and additionally, simple 1-D interpolation is used reconstruct the entire channels. This method has a reduced scattered pilot overhead, and is at least an order of magnitude less computationally complex

than some existing methods. In general, the proposed method of channel estimation is more robust in channels with high Doppler spread, and provides better performance than some existing methods and requires the less buffering of the OFDM symbols for the coherent detection at the receiver than in some methods.

The methods allow fewer pilot symbols to be placed within each OFDM symbol, while still allowing accurate interpolation of the channel response. The data rate of an MIMO-OFDM system is thereby improved.

A first broad aspect of the invention provides a method of inserting pilot symbols into Orthogonal Frequency Division Multiplexing (OFDM) frames at an OFDM transmitter having at least one transmitting antenna, the OFDM frames having a time domain and a frequency domain, each OFDM frame comprising a plurality of OFDM symbols. The method involves, for each antenna, inserting scattered pilot symbols in an identical scattered pattern in time-frequency.

In some embodiments, the identical scattered pattern is a regular diagonal-shaped lattice.

In some embodiments, inserting pilot symbols in an identical diagonal-shaped lattice involves for each point in the identical diagonal shaped lattice inserting a number of pilot symbols on a single sub-carrier for N consecutive OFDM symbols, where N is the number of transmitting antennae.

In some embodiments, diagonal shaped lattice is a diamond shaped lattice.

In some embodiments for each point in the diagonal-shaped lattice, L uncoded pilot symbols are



generated. Space time block coding (STBC) is performed on the group of L uncoded pilot symbols to produce an  $N \times N$  STBC block, L and N determining an STBC code rate. Then, one row or column of the STBC block is transmitted on each antenna  
5 on a specific sub-carrier.

In some embodiments, transmitting the pilot symbols is done with a power level greater than a power level of data symbols, depending upon a value reflective of channel conditions.

10 In some embodiments, transmitting the pilot symbols is done with a power level which is dynamically adjusted to ensure sufficiently accurate reception as a function of a modulation type applied to the sub-carriers carrying data.

15 In some embodiments, the diagonal shaped lattice pattern has a first plurality of equally spaced sub-carrier positions, and a second plurality of equally spaced sub-carrier positions offset from said first plurality. The pilot symbols are inserted alternately in time using the  
20 first plurality of equally spaced sub-carrier positions and the second plurality of equally spaced sub-carrier positions.

In some embodiments, the second plurality of sub-carriers is offset from the first plurality of equally  
25 spaced-sub-carrier positions by half the spacing between adjacent sub-carriers of the first plurality of sub-carrier positions thereby forming a diamond shaped lattice pattern.

In some embodiments, the pilot pattern is cyclically offset, both in a time direction and in a

frequency direction, for at least one adjacent base station to form re-use patterns.

Another broad aspect of the invention provides an OFDM transmitter. The OFDM transmitter has a plurality of  
5 transmit antennas, and is adapted to insert pilot symbols into Orthogonal Frequency Division Multiplexing (OFDM) frames having a time domain and a frequency domain, each OFDM frame comprising a plurality of OFDM symbols by, for each antenna, inserting pilot symbols in an identical  
10 scattered pattern in time-frequency.

In some embodiments, the identical scattered pattern is a diagonal-shaped lattice.

In some embodiments, inserting pilot symbols in an identical scattered pattern involves for each point in the  
15 identical scattered pattern inserting a number of pilot symbols on a single sub-carrier for N consecutive OFDM symbols, where N is the number of transmitting antennae, where  $N \geq 1$ .

In some embodiments, the scattered pattern is a  
20 diamond shaped lattice.

In some embodiments, for each point in the scattered pattern, the OFDM transmitter is adapted to generate L uncoded pilot symbols, perform space time block coding (STBC) on the group of L pilot symbols to produce an  
25  $N \times N$  STBC block, and transmit one row or column of the STBC block on each antenna.

In some embodiments, the OFDM transmitter is further adapted to transmit the pilot symbols with a power

level greater than a power level of data symbols depending on a value reflective of channel conditions.

In some embodiments in which the diamond shaped lattice pattern is employed, the diamond shaped lattice pattern has a first plurality of equally spaced sub-carrier positions and a second plurality of equally spaced sub-carrier positions offset from said first plurality. The pilot symbols are inserted alternately in time using the first plurality of equally spaced sub-carrier positions and the second plurality of equally spaced sub-carrier positions.

Another broad aspect of the invention provides a method of estimating a plurality of channel responses at an Orthogonal Frequency Division Multiplexing (OFDM) receiver having at least one receive antenna. The method involves at each receive antenna receiving OFDM frames transmitted by at least one transmitting antenna, the OFDM frames having a time domain and a frequency domain, the OFDM frames transmitted by each antenna having pilot symbols inserted in an identical scattered pattern in time-frequency, each OFDM frame comprising a plurality of OFDM symbols. For each transmit antenna, receive antenna combination: a) the pilot symbols of the received OFDM frames are used to estimate a channel response for each point in the scattered pattern; b) the channel response is estimated for of a plurality of points not on the scattered pattern by performing a two-dimensional (time direction, frequency direction) interpolation of channel responses determined for points in the scattered pattern; c) an interpolation is performed in the frequency direction to estimate the channel

responses corresponding to remaining OFDM sub-carriers within each OFDM symbol.

In some embodiments, a filtering function is performed on the channel responses prior to performing the  
5 interpolation in the frequency direction to estimate the channel responses corresponding to remaining OFDM sub-carriers within each OFDM symbol.

In some embodiments, estimating the channel response of a plurality of points not on the scattered  
10 pattern by performing a two-dimensional (time direction, frequency direction) interpolation of channel responses determined for points in the scattered pattern lattice involves for each sub-carrier to be estimated averaging  
15 channel responses of the given channel estimation period of a sub-carrier before the sub-carrier to be estimated in frequency (when present) and a sub-carrier after the sub-carrier to be estimated in frequency (when present) and the channel response for a previous estimation period (when present) and a following estimation period (when present).

20 In some embodiments, the method is applied to a single transmitter, single receiver system.

In other embodiments the method is applied to a single transmitter system wherein each point in the scattered pattern contains a single pilot symbol.

25 In some embodiments, the method is applied to a system in which there are  $N \geq 2$  antennas, and each point in the scattered pattern contains a number  $N$  of consecutive encoded pilot symbols transmitted on a sub-carrier, a single channel estimate being determined for each  $N$  encoded pilot  
30 symbols.

In some embodiments, the N encoded pilot symbols contain L pilot symbols which were STBC block coded, where N and L together determine a STBC code rate.

Other aspects and features of the present invention will become apparent to those ordinarily skilled in the art upon review of the following description of specific embodiments of the invention in conjunction with the accompanying Figures.

#### BRIEF DESCRIPTION OF THE DRAWINGS

10 The invention will now be described in greater detail with reference to the accompanying Figures, in which:

Figure 1 illustrates flow-charts for three examples of conventional OFDM Channel Estimation;

15 Figure 2 is a block diagram of a Multiple-Input Multiple-Output Orthogonal Frequency Division Multiplexing (OFDM) transmitter provided by an embodiment of the invention;

Figure 3 is a block diagram of an OFDM receiver;

20 Figure 4 is a flowchart of a method by which an OFDM transmitter inserts pilot symbols into an OFDM frame according to one embodiment of the invention;

Figure 5 is a diagram of a pilot pattern generated using the method of Figure 4;

25 Figure 6 is a block diagram of a MIMO system showing the channel transfer functions between two transmit antennas and two receive antennas;

Figure 7 is a time frequency diagram showing channel estimate positions for pilot channel estimation;

Figure 8 schematically illustrates a step of filtering estimated and interpolated pilot channel

5 estimates;

Figure 9 shows schematically the step of interpolating between the channel estimates previously determined to provide channel estimates for all sub-carriers and all times;

10 Figure 10 is a flow chart summarizing the overall channel estimation method provided by an embodiment of the invention; and

Figure 11 is an example of a set of performance results obtained using the method of Figure 10.

## 15 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The following sections describe a MIMO-OFDM transmitter/receiver and scattered pilot insertion. By way of introduction, a OFDM frame consists of the preamble OFDM symbols and regular OFDM symbols. Each OFDM symbol uses a

20 set of orthogonal sub-carriers. When there are two transmit antennas, two OFDM symbols form a STTD block. For regular OFDM symbols, some sub-carriers are used as pilot sub-carriers to carry pilot symbols while the others are used as data sub-carriers to carry data symbols. The pilot sub-

25 carriers are modulated by pilot symbols generated by QPSK. The data sub-carriers are modulated by complex data symbols generated by QAM mapping. STTD coding is applied to the pilot sub-carrier pairs located at the same frequency within one STTD block.

Referring to Figure 2, a block diagram of a Multiple-Input Multiple-Output (MIMO) Orthogonal Frequency Division Multiplexing (OFDM) transmitter provided by an embodiment of the invention is shown. The OFDM transmitter shown in Figure 2 is a two-output OFDM transmitter, though more generally there may be a plurality of  $M$  transmitting antennae. An OFDM transmitter 10 takes binary data as input but data in other forms may be accommodated. The binary data is passed to a coding/modulation primitive 12 responsible for encoding, interleaving, and modulating the binary data to generate data symbols, as is well known to those skilled in the art. The coding/modulation primitive 12 may include a number of processing blocks, not shown in Figure 2. An encoder 14 applies Space-Time Block Coding (SBTC) to the data symbols. The encoder 14 also separates the data symbols into a first processing path 16 and a second processing path 18, by sending alternate data symbols along each of the two processing paths. In the more general case in which the OFDM transmitter 10 includes  $M$  transmitting antennae, the encoder 14 separates the data symbols into  $M$  processing paths.

The data symbols sent along the first processing path 16 are sent to a first OFDM component 20. The data symbols are first passed to a demultiplexer 22 in the first OFDM component 20, after which the data symbols are treated as sub-carrier components. The data symbols are then sent to a pilot inserter 24, where pilot symbols are inserted among the data symbols. Collectively, the data symbols and pilot symbols are referred to hereinafter simply as symbols. The symbols are passed to an Inverse Fast Fourier Transform (IFFT) processor 26, then to a multiplexer 28 where they are recombined into a serial stream. A guard inserter 30 adds

prefixes to the symbols. Finally, the OFDM signals are passed through a hard limiter 32, a digital-to-analog converter 34, and a radio frequency (RF) transmitter 36 which transmits OFDM symbols as a signal through a first transmitting antenna 37. In most embodiments, each element in the first OFDM component 20 is a processor, a component of a larger processor, or a collection of processors or any suitable combination of hardware, firmware and software. These might include general purpose processors, ASICs, FPGAs, DSPs to name a few examples.

The pilot inserter 24 is connected to receive space-time coded pilot symbols from pilot STBC function 23 which performs STBC on pilot symbols 21. The pilot STBC block 23 takes two pilot symbols at a time for example  $P_1$  and  $P_2$  as indicated in Figure 2 and generates an STBC block consisting of a two by two matrix having  $(P_1, P_2)$  in the first row and having  $(-P_2^*, P_1^*)$  in the second row. It is the first row of this STBC block that is inserted by the pilot inserter 24.

The data symbols sent along the second processing path 18 are sent to a second OFDM component 38 which includes processors similar to those included in the first OFDM component 20. However, the pilot inserter 40 inserts encoded pilot symbols from the second row of the STBC block produced by the pilot STBC function 23. The symbols sent along the second processing path 18 are ultimately transmitted as a signal through a second transmitting antenna 42.

Referring now to Figure 3, a block diagram of an MIMO-OFDM receiver is shown. An OFDM receiver 50 includes a first receiving antenna 52 and a second receiving antenna 54



(although more generally there will be one or more receiving antennae). The first receiving antenna 52 receives a first received signal. The first received signal is a combination of the two signals transmitted by the two transmitting antennae 37 and 42 of Figure 2, although each of the two signals will have been altered by a respective channel between the respective transmitting antenna and the first receiving antenna 52. The second receiving antenna 54 receives a second received signal. The second received signal is a combination of the two signals transmitted by the two transmitting antennae 37 and 42 of Figure 2, although each of the two signals will have been altered by a respective channel between the respective transmitting antenna and the second receiving antenna 54. The four channels (between each of the two transmitting antennae and each of the two receiving antennae) may vary with time and with frequency, and will usually be different from each other.

The OFDM receiver 50 includes a first OFDM component 56 and a second OFDM component 58 (although in general there will be  $N$  OFDM components, one for each receiving antenna). The first OFDM component 56 includes a RF receiver 59, and an analog-to-digital converter 60, which converts the first received signal into digital signal samples. The signal samples are passed to a frequency synchronizer 62 and a frequency offset corrector 64. The signal samples are also fed to a frame/time synchronizer 66. Collectively, these three components produce synchronized signal samples.

The synchronized signal samples represent a time sequence of data. The synchronized signal samples are

passed to a demultiplexer 68, then passed in parallel to a Fast Fourier Transform (FFT) processor 70. The FFT processor 70 performs an FFT on the signal samples to generate estimated received symbols which are multiplexed in  
5 MUX 76 and sent as received symbols to decoder 78. Ideally, the received symbols would be the same as the symbols fed into the IFFT processor 26 at the OFDM transmitter 10. However, as the received signals will have likely been altered by the various propagation channels, the first OFDM  
10 component 56 must correct the received symbols by taking into account the channels. The received symbols are passed to a channel estimator 72, which analyses received pilot symbols located at known times and frequencies within the OFDM frame. The channel estimator 72 compares the received  
15 pilot symbols with what the channel estimator 72 knows to be the values of the pilot symbols as transmitted by the OFDM transmitter 10, and generates an estimated channel response for each frequency and time within the OFDM symbol. The estimated channel responses are passed to decoder 78. The  
20 channel estimator 72 is described in detail below.

The second OFDM component 58 includes similar components as are included in the first OFDM component 56, and processes the second received signal in the same manner as the first OFDM component 56 processes the first received  
25 signal. Each OFDM component passes OFDM symbols to the decoder 78.

The decoder 78 applies STBC decoding to the OFDM symbols, and passes the symbols to a decoding/demodulating primitive 80 responsible for decoding, de-interleaving, and  
30 demodulating the symbols to generate output binary data, as is well known to those skilled in the art. The

decoding/demodulation primitive 80 which may include a number of additional processing blocks, not shown in FIG. 2. Each element in the OFDM components 56 and 58 is a processor, a component of a larger processor, or a collection of processors.

Referring now to Figure 4, a method by which each of the pilot inserters 24 and 40 of Figure 2 inserts pilot symbols among the data symbols is shown. The method will be described with reference to the pilot inserter 24 in the first OFDM component 20. At step 100, the pilot inserter 24 receives data symbols from the demultiplexer 22. At step 102 the pilot STBC function 23 generates (or receives) two pilot symbols. At step 104 the pilot STBC function 23 applies STBC encoding to the pilot symbols, so as to generate an STBC block of encoded pilot symbols. The encoded pilot symbols generated for the first transmitting antenna 37 will be one row of the STBC block and will have a number equal to the number of transmitting antennae in the OFDM transmitter. Thus, for a two antenna system a  $2 \times 2$  STBC block is generated.

At step 106 the pilot inserter 24 inserts the encoded pilot symbols within the OFDM symbol. Encoded pilot symbols are inserted in a diamond lattice pattern. The diamond lattice pattern uses the same frequencies as the other diamond lattice patterns, but has a temporal offset from the other diamond lattice patterns. Preferably, the temporal offset for each diamond lattice pattern is one symbol (in the time direction) from another diamond lattice pattern, so that the diamond lattice patterns use consecutive symbols in the time direction of the OFDM frame.

The diamond lattice pattern in which each encoded pilot symbol is inserted within the OFDM frame is preferably a perfect diamond lattice pattern. To achieve this, the encoded pilot symbol is inserted at each of a first subset of frequencies. The frequencies within the first subset of frequencies are spaced equally apart by a pilot spacing. The encoded pilot symbol is inserted at each of the first subset of frequencies for an STBC block (two OFDM symbols). At some later time, the encoded pilot symbols are inserted at each of a second subset of frequencies. The frequencies within the second subset of frequencies are shifted from the frequencies within the first subset of frequencies by half of the pilot spacing within the frequency direction. The pilot inserter 24 continues to insert encoded pilot symbols, alternating between the first subset of frequencies and the second subset of frequencies.

Alternatively, a different pilot pattern can be used, as long as the same pilot pattern is used for each of the at least one encoded pilot symbols unique to the transmitting antenna 37, and as long as the pilot patterns for the encoded pilot symbols are offset from each other in the time direction of the OFDM frame. For example, a regular diagonal lattice pattern may be used, the diamond shaped lattice being a special case of this.

The pilot inserter 40 inserts pilot symbols using the same method, although the pilot symbols will be the other half of the STBC block 42. The encoded pilot symbols unique to the second transmitting antenna 42 are inserted in the OFDM frame at the same symbol locations at which the encoded pilot symbols corresponding to the first transmitting antenna 37 are inserted.

Referring to Figure 5, an example pilot pattern generated using the method of Figure 4 is shown. Pilot and data symbols are spread over the OFDM frame in a time direction 120 and a frequency direction 122. Most symbols within the OFDM frame are data symbols 124. A first set of encoded pilot symbols 126 corresponding to the first transmitting antenna 37 is inserted in a diamond lattice pattern. A second set of encoded pilot symbols 128 corresponding to the first transmitting antenna 37 is inserted in a diamond lattice structure at the same frequencies as the first set of encoded pilot symbols, but offset by one OFDM symbol location in the time direction 120. In the illustrated example two of every four OFDM symbols carry encoded pilot symbols. Each other transmitting antenna transmits using the same pattern. The pairs of consecutive pilot symbols on a sub-carrier consist of two raw pilot symbols STBC encoded. The same pattern is transmitted by the second antenna.

The power of the encoded pilot symbols 126, 128 may be increased compared to the traffic data symbol 124. The power increase of the encoded pilot can be dynamically adjusted with respect to the transmitting data symbol power level or modulation type (QAM size), or as a function of channel quality. The location of diamond lattice pattern may also be optimized to allow a fast extraction of scattered pilot without using the computing. This may be achieved if the pilot subcarriers are spaced in the frequency direction by  $2^n$ . In the multiple base station transmission arrangement, the location of the diamond lattice pattern can be cyclic offset both in time direction and in frequency direction amongst adjacent base stations to form a diamond lattice re-use pattern.

Referring now to Figures 6 to 10, a channel estimation method is described which is based on the pilot insertion method above. This invention presents a simple 2-dimensional channel interpolator for MIMO-OFDM system with low pilot density for fast fading channels both in time and in frequency. The goal of channel estimation is to estimate the channel characteristics for each sub-carrier and at each time for each possible transmit antenna, receive antenna combination. Referring to Figure 13, for the two transmit antenna, two receive antenna example, shown are two transmit antennas Tx1 140 and Tx2 142 and two receive antennas Rx1 144 and Rx2 146. Channel estimation estimates a channel for each sub-carrier and at each time between Tx1 140 and Rx1 144 indicated as each  $H_{11}$  148, a channel between Tx1 140 and Rx2 146 indicated by transfer function  $H_{12}$  150, a channel estimate for transmitter Tx2 142 to Rx1 144 indicated as transfer function  $H_{21}$  152 and finally, a channel estimate for transmitter Tx2 142 to receiver Rx2 146 indicated as transfer function  $H_{22}$  154.

Some advantages for the proposed method compared to some existing methods are: (1) robust to high mobility-speed (2) a reduction of the scattered pilot grid density and therefore a reduction of the pilot overhead.

Let  $P_1$  and  $P_2$  be the two pilot symbols encoded in an STBC block and transmitted by two antennas on one sub-carrier in consecutive OFDM symbols. Then at the first receive antenna, the following relationship exists for each sub-carrier on which pilot symbols are transmitted, where it is assumed the channel response  $H_{ij}$  is constant over two OFDM frames:

$$\begin{bmatrix} Y_{1,1} \\ Y_{1,2} \end{bmatrix} = \begin{bmatrix} P_1 & P_2 \\ -P_2^* & P_1^* \end{bmatrix} \begin{bmatrix} H_{11} \\ H_{21} \end{bmatrix}$$

Y<sub>1,1</sub> is the received data on the first antenna on the sub-carrier in the first of the two consecutive OFDM symbols, and Y<sub>1,2</sub> is the received data on the first antenna  
 5 on the sub-carrier in the second of the two consecutive symbols. This can be solved for H<sub>11</sub>, H<sub>21</sub> to yield:

$$\begin{bmatrix} H_{11} \\ H_{21} \end{bmatrix} = \frac{1}{|P_1|^2 + |P_2|^2} \begin{bmatrix} P_1^* & -P_2 \\ P_2^* & P_1 \end{bmatrix} \begin{bmatrix} Y_{1,1} \\ Y_{1,2} \end{bmatrix}$$

A similar process for the second antenna yields

$$\begin{bmatrix} H_{12} \\ H_{22} \end{bmatrix} = \frac{1}{|P_1|^2 + |P_2|^2} \begin{bmatrix} P_1^* & -P_2 \\ P_2^* & P_1 \end{bmatrix} \begin{bmatrix} Y_{2,1} \\ Y_{2,2} \end{bmatrix}$$

10 where Y<sub>2,1</sub> is the received data on the second antenna on the sub-carrier in the first of the two consecutive OFDM symbols, and Y<sub>2,2</sub> is the received data on the second antenna on the sub-carrier in the second of the two consecutive OFDM symbols.

15 Using this techniques, a channel estimate is made for each pilot sub-carrier, and for each pair of OFDM symbols used to transmit STBC blocks.

For the example of Figure 12, the result is a channel estimate, for each of the possible channels (these  
 20 are for channels in this example as shown in Figure 13) for each pair of pilot symbols transmitted. This is illustrated in Figure 14 where only sub-carriers used to transmit pilots are shown. A channel estimate 150 is generated for each pair of (consecutive in time) OFDM frames for each pilot  
 25 sub-carrier. This results in channel estimates 150, 152,

154 for the first and second frames, and channel estimates  
156, 158, 160 for the fifth and sixth frames and so on.

The channel estimates are made on a STBC block by  
block basis so that the pattern of channel estimate shown in  
5 Figure 7 develops over time. The next step in the process  
is to perform an interpolation based on the channel estimate  
of Figure 7 to obtain channel estimates for the places in  
Figure 7 which do not represent pilot channel positions.  
The manner in which this is done will be described for a  
10 single example, namely the unknown channel estimate  
indicated at 163 of Figure 7. Channel estimates are  
buffered on an ongoing basis and when the four channel  
estimates 152, 156, 158 and 164 forming a diamond 162  
surrounding the unknown channel estimate 163 have been  
15 computed, it is time to interpolate to obtain a channel  
estimate for the unknown point 163. The channel transfer  
function at the sub-carrier located at the centre of the  
diamond can be obtained from a simple 4 points two-  
dimensional interpolator. Three points two-dimensional  
20 interpolators can be used to obtain the channel estimates  
corresponding to the first or last useful sub-carrier:

$$H_{new}(n+1, k) = \frac{1}{4}(H(n, k) + H(n+2, k) + H(n+1, k-1) + H(n+1, k+1))$$

where  $(k=2, \dots, N_{pilot}-1)$

$$H_{new}(n+1, 1) = \frac{1}{4}(H(n, 1) + H(n+2, 1) + 2H(n+1, 2))$$

$$25 \quad H_{new}(n+1, N_{pilot}) = \frac{1}{4}(H(n, N_{pilot}) + H(n+2, N_{pilot}) + 2H(n, N_{pilot}-1))$$

where  $k$  is the pilot sub-carrier index,  $n$  is the channel  
estimate index (or STBC block number - one channel estimate  
per sub-carrier for every two symbols), and  $N_{pilot}$  is the  
number of pilot sub-carriers (6 in the example of Figure 7).



$H_{\text{new}}$  is the newly interpolated channel estimate for the  $i^{\text{th}}$  channel estimation period, and the  $j^{\text{th}}$  pilot sub-carrier.

$H(i, j)$  is the channel estimate determined as described previously from the pilot symbols. A three points

- 5 interpolator would also be performed for the last STBC blocks in the OFDM frame (i.e. the last two OFDM symbols).

These calculations are done for each transmit antenna, receiver antenna combination. It is noted that this is just one example of how the channel estimates can be  
10 interpolated.

If the original distance between pilot sub-carriers in the frequency direction is  $D_f$ , after first step of interpolation described above, the pilot sub-carriers' separation becomes  $\frac{D_f}{2}$ .

- 15 In some embodiments, to remove noise, the channel estimates thus computed are filtered at each channel estimation period. This is shown in Figure 6 where the channel estimates 170 for one channel estimation period are shown entering filter 172 to produce filtered channel  
20 estimates. For example, a simple 3 point moving iterative smoothing algorithm may be applied to  $H'$ :

$$H'_{sm}(n, k) = H'_{sm}(n, k-1) + \frac{1}{3}(H'(n, k+1) + H'_{sm}(n, k-2))$$

where  $k=3, \dots, 2 N_{\text{pilot}}-2$ . It is to be understood that other filtering algorithms may be employed.

- 25 After the interpolation of the pilot channel estimate as summarized in Figure 7, there will be a channel estimate for each sub-carrier on which pilot channel information was transmitted and for each two OFDM symbol

period over which pilot channelling information was transmitted. Referring to Figure 5, this means that there will be a channel estimate for each antenna for time frequency points which are shaded to indicate that pilot channel information was transmitted. There will also be channel estimates for the time frequency point in the centre of the diamond shaped lattice structure of Figure 7. However, for points which are not pilot symbol transmission time-frequency points nor points which are at the centre of a diamond shaped lattice of such points, there will be no channel estimate yet computed. The next step is to perform a further interpolation step to develop channel estimates for these other points.

In some embodiments, Cubic Lagrange interpolation and linear interpolation (for the sub-carriers near the first and the last useful sub-carrier) in the frequency direction are used to obtain the channel transfer function at all sub-carriers for each STBC block (for each pair of OFDM symbols).

The coefficients of the Cubic Lagrange interpolator can be calculated as

$$\begin{aligned}\mu(i) &= \frac{i}{D_f/2} & i &= 1, 2, \dots, \frac{D_f}{2} \\ q_{-1}(\mu) &= -\frac{1}{6}\mu^3 + \frac{1}{2}\mu^2 - \frac{1}{3}\mu \\ q_0(\mu) &= \frac{1}{2}\mu^3 - \mu^2 - \frac{1}{2}\mu + 1 \\ q_1(\mu) &= -\frac{1}{2}\mu^3 + \frac{1}{2}\mu^2 + \mu \\ q_2(\mu) &= -\frac{1}{6}\mu^3 - \frac{1}{6}\mu\end{aligned}$$

The channel transfer functions at data sub-carriers are given by

$$H_{interp}((j-1) \cdot \frac{D_f}{2} + i) = \sum_{n=1}^2 q_n(\mu(i)) H'_{im}(j+n)$$

where  $j=2, \dots, N_{pilot}-2$ .

This is illustrated in Figure 9 where the  
 5 estimated channel responses are fed to the Lagrange cubic  
 interpolator function 175 which outputs values for all  
 intermediate sub-carriers. Other interpolations may  
 alternatively be employed.

In some embodiments, every OFDM symbol contains  
 10 some pilot insertion points and as such this completes the  
 interpolation process. In other embodiments, there are some  
 OFDM symbols which do not have any pilot insertion points.  
 To get channel estimates for these OFDM symbols, an  
 interpolation in time of the previously computed channel  
 15 estimates is performed. In high mobility applications,  
 pilots should be included in every OFDM symbol avoiding the  
 need for this last interpolation in time step.

Figure 10 presents an overall block diagram of the  
 interpolation method proposed for two transmit antennas. An  
 20 example set of performance results for the proposed MIMO-  
 OFDM channel estimation algorithm is shown in Figure 10. The  
 performance of the 2-D channel estimation algorithm is close  
 to the performance of ideal channel (only 0.5dB loss) at  
 very high Doppler spread.

Referring now to Figures 10 and 3, the channel  
 25 estimation method is carried out by the channel estimator 72  
 in order to estimate a channel response for each sub-carrier  
 and each OFDM symbol within an OFDM frame. The channel  
 estimation method starts at step 500 by extracting the pilot  
 30 symbols in the frequency domain for each receive antenna.  
 This is followed by a channel response matrix computing step

502; whereby the received signal received by the receiving antenna is decoded, which in effect performs a time average of the encoded pilot symbols at each point in the pilot pattern. For example, suppose the receiving antenna  
5 receives an OFDM frame having a pilot pattern as shown in Figure 5 (although the symbol 126 will now be a linear combination of the encoded pilot symbol transmitted at this location by each of the transmitting antenna, and the symbol 128 will be a linear combination of the encoded pilot symbol  
10 transmitted at this location by each of the transmitting antenna). Following decoding, the pilot symbol at symbol location 126 will be an average of the pilot symbol received at symbol location 126 and the pilot symbol received at symbol location 128. The time averaging effect produced by  
15 the STBC decoding, during step 503, can be viewed as a pre-processing step, as can steps 500 and 502. The actual channel estimation method can be described broadly in four steps. Following step 503, during step 504 the channel estimator 72 estimates the channel response for each of a  
20 plurality of pilot symbols. For a diamond lattice pattern, the plurality of pilot symbols will be four pilot symbols forming a single diamond pattern. The channel estimator 72 estimates the channel response of a central symbol, the central symbol having a time direction value and a frequency  
25 direction value bounded by the time direction values and the frequency direction values of the plurality of pilot symbols. The central symbol preferably has a frequency direction value equal to the frequency direction values of two of the plurality of pilot symbols, and has a time  
30 direction value midway between the time direction values of the two pilot symbols having the same frequency direction value as the central symbol. This can generally be described as a four-point 2-D interpolation of the channel

response between pilot symbols. Third, the channel estimator 72 smoothes the channel responses (corresponding to both encoded pilot symbols and to the central symbol) in the frequency direction, preferably by performing a three-point smoothing, as per step 505. Fourth, the channel estimator 72 performs an interpolation in the frequency direction to estimate the channel response for remaining symbols, as per step 506. The interpolation may be a linear interpolation for symbols having a frequency direction value equal to a first or a last useful sub-carrier within the OFDM symbol, and a cubic Lagrange interpolation otherwise.

The method of inserting pilot symbols (described above with reference to Figure 4) and the channel estimation method (described above with reference to Figure 10) need not be used together. Any channel estimation method may be used by the OFDM receiver to estimate the channel responses for an OFDM frame containing encoded pilot symbols inserted using the method described above. However, due to the sparse distribution of the pilot symbols in the pilot pattern described above with reference to Figure 4 and Figure 5, a two-dimensional interpolation method is preferable over a one-dimensional interpolation method. Similarly, the channel estimation method may be applied to an OFDM frame containing any pattern of pilot symbols.

The invention has been described with respect to an MIMO-OFDM communication system. The invention may also be used with advantage in a single input-multiple output OFDM communication system, as the method of inserting pilot symbols (described with reference to Figure 4) and the channel estimation method (described with reference to Figure 10) do not depend on the number of receiving antenna.

Each receiving antenna within the OFDM receiver 50 performs channel estimation independently, regardless of the number of receiving antennae present.

The channel estimation method described with  
5 reference to Figure 10 will also be advantageous in an OFDM communication system having only one transmitting antenna, as the method provides an improved interpolation of the channel response regardless of the number of transmitting antenna. The method of inserting pilot symbols described  
10 with reference to Figure 11 may be used in an OFDM communication system having only one transmitting antenna, but will not be as advantageous as in an OFDM communication system having more than one transmitting antenna as there will be no reduction in overhead.

15 The method of inserting pilot symbols and the channel estimation method are preferably implemented on the OFDM transmitter and on the OFDM receiver respectively in the form of software instructions readable by a digital signal processor. Alternatively, the methods may be  
20 implemented as logic circuitry within an integrated circuit. More generally, any computing apparatus containing logic for executing the described functionality may implement the methods. The computing apparatus which implements the methods (in particular the pilot inserter or the channel  
25 estimator) may be a single processor, more than one processor, or a component of a larger processor. The logic may comprise external instructions stored on a computer-readable medium, or may comprise internal circuitry.

What has been described is merely illustrative of  
30 the application of the principles of the invention. Other arrangements and methods can be implemented by those skilled

in the art without departing from the spirit and scope of  
the present invention.

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